

We claim:

1. An imaging apparatus comprising:
 - a container for a liquid;
 - a transmitter for transmitting wavefield energy into the liquid and a tissue appendage of a body of a mammal;
 - a device holding the tissue appendage stationary relative to the liquid in the container;
 - a receiver to receive wavefield energy transmitted through the tissue appendage;
 - and
 - an image renderer to process the received wavefield energy to render therefrom an image of the tissue appendage.
2. The imaging apparatus as defined in Claim 1, wherein the receiver receives wavefield energy transmitted from the transmitter through both the liquid and the tissue appendage.
3. The imaging apparatus as defined in Claim 1, wherein the receiver receives incident wavefield energy that has been transmitted:
 - from the transmitter into the liquid in the container;
 - from the liquid in the container into the device for holding the tissue appendage;
 - from the device for holding the tissue appendage into the tissue appendage;
 - from the tissue appendage into the device for holding the tissue appendage;
 - from the device for holding the tissue appendage into the liquid; and
 - from the liquid to the receiver.

4. The imaging apparatus as defined in Claim 1, wherein the device is assisted by pressure in holding the tissue appendage stationary relative to the liquid in the container.

5. The imaging apparatus as defined in Claim 1, wherein the device for holding the tissue appendage reduces movement of the tissue appendage relative to the liquid in the container during movement of the body of the animal.

6. The imaging apparatus as defined in Claim 1, wherein:
the liquid is water;
the tissue appendage is a breast; and
the animal is a human.

7. The imaging apparatus as defined in Claim 1, wherein the device includes a membrane that covers a surface on the tissue appendage.

8. The imaging apparatus as defined in Claim 2, wherein the wavefield energy that is received by the receiver is transmitted from the transmitter is processed by the image renderer in an inverse scattering parabolic propagation step.

9. The imaging apparatus as defined in Claim 8, wherein:
the wavefield energy that is received by the receiver has both a wavelength in the liquid and a corresponding wavefield frequency component in the liquid;

the inverse scattering parabolic propagation step that is accelerated in speed by employing a computational pixel size that is greater than one half of the wavelength of the corresponding wavefield frequency component.

10. The imaging apparatus as defined in Claim 9, wherein the inverse scattering parabolic propagation step is implemented by using a short convolution operation.

11. The imaging apparatus as defined in Claim 10, wherein the short convolution operation is a discrete convolution which is faster if done by direct summation rather than by a Fast Fourier Transform (FFT).

12. The imaging apparatus as defined in Claim 9, wherein the inverse scattering parabolic propagation step is implemented by using an FFT.

13. The imaging apparatus as defined in Claim 2, wherein:
the wavefield energy that is received by the receiver is transmitted from the transmitter and has a wavelength in the liquid in the container corresponding to a corresponding maximum temporal frequency; and
the image renderer performs an inverse scattering parabolic propagation step that is accelerated in speed by employing a computational pixel size that is greater than one half of the wavelength of the corresponding maximum temporal frequency.

14. The imaging apparatus as defined in Claim 2, wherein:
the image of the tissue appendage has a plurality of image components;

the wavefield energy that is received by the receiver is transmitted from the transmitter:

has a wavelength in the liquid in the container corresponding to a corresponding maximum temporal frequency; and

is discretized by a plurality of points each being separated from other said points by an average spatial separation;

the image renderer performs imaging method which totally or partially uses wave equation modeling, wherein:

the wave equation modeling utilizes a nonlinear operator relating an inversion data to the plurality of image components;

the inversion data is a transformation of the received wavefield energy and is within the range of the nonlinear operator;

the domain of the nonlinear operator is the image components;

the imaging method uses an arithmetic operation which computes the received wavefield energy on a set of surfaces given the wavefield energy on another, disjoint set of surfaces using a parabolic differential equation in the derivation of the arithmetic operation; and

the imaging method is accelerated in speed by employing the average spatial separation of the points to be greater than one half the wavelength in the liquid.

15. The imaging apparatus as defined in Claim 14, wherein the imaging method is implemented by using a short convolution operation.

16. The imaging apparatus as defined in Claim 15, wherein the short convolution operation is a discrete convolution which is faster if done by direct summation rather than by a Fast Fourier Transform (FFT).

17. The imaging apparatus as defined in Claim 14, wherein the imaging method is implemented by using an FFT.

18. A breast imaging apparatus comprising:
a water tank;
means for immobilizing a breast surface relative to water in the water tank,
wherein the breast surface is contiguous with the body of a mammal;
means for irradiating the breast surface with wavefield energy;
means for receiving the wavefield energy; and
means for processing the received wavefield energy to render an image of tissue beneath the breast surface.

19. The breast imaging apparatus as defined in Claim 18, wherein the means for immobilizing a breast surface is assisted by pressure in holding the breast surface in and stationary to the water in the water tank.

20. The breast imaging apparatus as defined in Claim 19, wherein:
the means for immobilizing a breast surface includes a membrane that covers the breast surface; and
the pressure is applied to the membrane.

21. The breast imaging apparatus as defined in Claim 19, wherein:
the wavefield energy that is received by the receiver is transmitted from the transmitter; and
the means for processing the received wavefield energy to render an image of tissue beneath the breast surface performs an inverse scattering parabolic propagation step.
22. The breast imaging apparatus as defined in Claim 21, wherein:
the wavefield energy that is received by the receiver has both a wavelength in the liquid and a corresponding wavefield frequency component in the liquid;
the inverse scattering parabolic propagation step that is accelerated in speed by employing a computational pixel size that is greater than one half of the wavelength of the corresponding wavefield frequency component.
23. The breast imaging apparatus as defined in Claim 19, wherein:
the wavefield energy that is received by the receiver is transmitted from the transmitter and has both a wavelength in the water and a corresponding wavefield frequency component;
the means for processing the received wavefield energy to render an image of tissue beneath the breast surface performs an inverse scattering parabolic propagation step that is accelerated in speed by employing a computational pixel size that is greater than one half of the wavelength in the water of the corresponding wavefield frequency component.

24. The breast imaging apparatus as defined in Claim 22, wherein the inverse scattering parabolic propagation step is implemented by using a short convolution operation.

25. The breast imaging apparatus as defined in Claim 24, wherein the short convolution operation is a discrete convolution which is faster if done by direct summation rather than by Fast Fourier Transform (FFT).

26. The breast imaging apparatus as defined in Claim 22, wherein the inverse scattering parabolic propagation step is implemented by using a FFT.

27. A method of imaging a mammalian breast appendage, the method comprising:

immobilizing a mammalian breast appendage in a liquid bath relative to the liquid bath;

irradiating the liquid bath and the mammalian breast appendage with wavefield energy;

receiving at a receiver a received wavefield energy that is transmitted through both the liquid bath and the mammalian breast appendage; and

using the received wavefield energy to render an image of the mammalian breast.

28. The method as defined in Claim 27, wherein the using the received wavefield energy to render an image of the mammalian breast comprises using an inverse scattering parabolic propagation step.

29. The method as defined in Claim 28, wherein:

the received wavefield energy has a wavelength in the liquid bath and a corresponding wavefield frequency component; and

the inverse scattering parabolic propagation step is accelerated in speed by employing a computational pixel size that is greater than one half of the wavelength in the liquid bath of the corresponding wavefield frequency component.

30. The method as defined in Claim 27, wherein the mammalian breast appendage is immobilized in the liquid bath by a pressure applied to a surface of the mammalian breast appendage.

31. A method for producing an image of an object in a region from wavefield energy that has been transmitted into and scattered by the object, said image comprising a map of selected physical characteristics at selected points within the region, said image being stored in a computer memory, and said method comprising the steps of:

(a) transducing an electric signal at each of one or more frequencies into wavefield energy propagated with respective wavelengths from one or more of transmitter transducer positions, each said transmitter transducer position propagating wavefield energy at at least one orientation defined by Euler angles with respect to a selected fixed coordinate system;

(b) for one or more receiver positions each having at least one orientation defined by Euler angles with respect to said selected fixed coordinate system, detecting at each of said one or more receiver positions and respective orientations thereof said wavefield energy;

- (c) electronically processing said detected wavefield energy so as to transform said detected wavefield energy into one or more reception stored signals stored in said computer memory and corresponding to a scattered wavefield energy detected;
- (d) setting a region characteristics estimate of selected physical characteristics at selected image points within the region and storing each said region characteristics estimate in said computer memory;
- (e) performing a convergence step comprising the following steps:
 - (1) preparing, for each said one or more frequencies at each said transmitter transducer positions and respective orientations thereof; an estimate of a total wavefield energy at selected wavefield points derived from a selected incident wavefield energy for a subset of said selected wavefield points stored in the computer memory and said region characteristics estimate for said selected image points by the steps of:
 - (i) designating a primary subset of said selected wavefield points and a different secondary subset of said selected wavefield points, each said selected wavefield point in the primary and secondary subsets of said selected wavefield points being separated from any other by at least one half of a minimum wavelength, wherein the minimum wavelength is the wavelength of the wavefield energy in the region at the maximum of said one or more frequencies;
 - (ii) setting the estimate of the total wavefield energy equal to a selected initial total wavefield energy estimate for the primary subset of said selected wavefield points;

(iii) computing the estimate of the total wavefield energy on the secondary subset of said selected wavefield points using the region characteristics estimate on the selected image points and the total wavefield energy on the primary subset of said selected wavefield points;

(iv) re-designating the primary subset of said selected wavefield points to include a subset of the secondary subset of said selected wavefield points and re-designating the secondary subset of said selected wavefield points to include another subset of the selected wavefield points, each said selected wavefield point in the primary and secondary subsets of said selected wavefield points being separated from any other by at least one half of a minimum wavelength, wherein the minimum wavelength is the wavelength of the wavefield energy in the region at the maximum of said one or more frequencies; and

(v) repeating steps ((iii) through ((iv)) until the estimate of the total wavefield energy is computed for each of the selected wavefield points;

(2) deriving, for each of said one or more frequencies at each said transmitter transducer position and orientations thereof; a calculated scattered wavefield energy for one or more of said receiver positions and respective orientations thereof from at least one of said region characteristics estimate at said selected image points and said estimate of said total wavefield energy for a corresponding transmitter transducer position and orientations thereof at a portion of said selected wavefield points by performing the steps of:

- (i) for each selected point of a portion of the selected wavefield points, said portion of the selected wavefield points corresponding to one of said one or more receiver positions and respective orientations thereof; setting said calculated scattered wavefield energy equal to the estimate of the total wavefield energy less said selected incident wavefield energy; and
 - (ii) computing a sum over said portion of said selected wavefield points equal to the sum of the calculated scattered wavefield energy for said portion of said selected wavefield points times a function constructed to correspond to one or more of said one or more receiver positions and respective orientations thereof;
- (3) for each said transmitter transducer position and orientations thereof and for each said receiver position and orientation thereof comparing said scattered wavefield energy detected to said calculated scattered wavefield energy to derive therefrom a comparator; and
- (4) when said comparator is greater than a selected tolerance, determining and storing in said computer memory said region characteristics estimate by computing one or more derivatives of the comparator or approximations thereof with respect to one or more of said selected physical characteristics at one or more of said selected image points, and then using said one or more derivatives of the comparator or approximations thereof to compute a region characteristics correction, and then adding said region characteristics correction to each of said region characteristics estimate for each of said one or more of said selected

image points, wherein said one or more derivatives of the comparator or approximations thereof is computed from one or more of:

- (i) at each said one or more frequencies, said estimate of said total wavefield energy for a portion said selected wavefield points for each of said one or more of said transmitter transducer positions and respective orientations thereof;
 - (ii) at each of said one or more frequencies, said calculated scattered wavefield energy for said one or more receiver positions and respective orientations thereof; and for each of said one or more of said transmitter transducer positions and respective orientations thereof;
 - (iii) at each of said one or more frequencies, said scattered wavefield energy detected for said one or more receiver positions and respective orientations thereof and for each of said one or more of said transmitter transducer positions and respective orientations thereof; and
 - (iv) said region characteristics estimate for said selected image points;
- (f) repeating said convergence step until said comparator is less than or equal to said selected tolerance, and thereafter storing said region characteristics estimate as said image in the computer memory.

32. The method as defined in Claim 31, further comprising, prior to the transducing an electric signal at each of one or more frequencies, compressing a human breast between two opposing plates, wherein the wavefield energy is:

propagated into one plate, through the human breast, and out of the other plate,
and
detected outside the other plate.

33. The method as defined in Claim 31, further comprising, prior to the transducing an electric signal at each of one or more frequencies, compressing a human breast between first and second opposing plates and between third and fourth opposing plates, wherein:

the first and third plates and the second and fourth plates are respectively orthogonal;

the second and fourth plates reflect the propagated wavefield energy; and

the wavefield energy is:

propagated into the first plate, through the human breast, and out
of the second plate, and
detected outside the second plate.

34. The method as defined in Claim 31, wherein:

the object in the region is a mammalian breast appendage in a liquid bath; and

the method further comprises, prior to the transducing an electric signal at each of one or more frequencies, immobilizing the mammalian breast with a constraining device relative to the liquid bath, wherein the wavefield energy is:

propagated into each of the liquid bath and the human breast, and
detected after passing through the human breast.

35. A computer-readable medium having computer-executable instructions,
which when executed on a processor, direct a computer to perform the steps of Claim 31.